Using Surface Current Models to Predict Particle Movement in the Eastern Basin of the Juan de Fuca Strait: Implications for Marine Protected Area Design

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Abstract
The eastern basin of the Strait of Juan de Fuca has been hypothesized to serve as a collection and dispersal zone for larvae. Lagrangian transport of surface particles was investigated using a tidal circulation model of surface heights and currents for the entire region. Paths and endpoints of passive drifters were simulated for four points of origin in the eastern basin over a period of one to four weeks. Results show that virtual drifters are strongly influenced by tidal cycles, with high retention at specific locations within the eastern basin, both on- and offshore. Offshore points of concentration include the southern opening of Rosario and Haro Straits, the leeward side of Dungeness Spit, the area where the eastern and western sides of the Strait of Juan de Fuca meet just south of Victoria, and the western shore of San Juan Island. Onshore landings correspond with results from empirical drifter studies conducted previously. Simulations indicate within-basin central retention over temporal scales that correspond to the larval lifespan of many taxa. This finding has potential importance to marine populations throughout the entire Georgia Basin ecosystem. Larval collection zones feed higher trophic levels and associated food webs. Given the high potential for successful larval linkages and areas of both import and export within the basin, these results further imply that a functional network of marine protected areas could be developed in the Georgia Basin region.

Introduction
In Washington State, many efforts to address the declining health of marine resources are currently directed toward establishing marine protected areas (MPAs). San Juan County alone has 100 protected sites, both regulatory and voluntary, if one uses the least restrictive definition of the term (Murray 1998). Existing MPAs confer variable levels of protection; in some areas, resource protection is virtually nonexistent.

Of continuing high priority on governmental and organizational agendas are the mapping, design and assessment of MPAs (e.g., Northwest Straits 2000; Murray 1998), as well as the design of MPA *networks*. One especially difficult aspect of network design is ensuring adequate levels of larval supply and retention (Roberts 2003; Carr et al, 2003). Here we address the potential for larval retention in the eastern basin of the Strait of Juan de Fuca.

The location of many of these MPAs has been largely based on feasibility and opportunity. It is our contention that MPA network design and resource management goals in the SJA would benefit from increased attention to relevant physical and biological factors. To this end, biophysical models that incorporate local ocean circulation as well as behavioral characteristics can play an important role in understanding the ecological nature of the region.

The eastern Strait of Juan de Fuca is an important oceanographic, ecological, and economic component within the Puget Sound/Georgia Basin region. In this paper, we explore the possibility of important central (offshore) larval collection zones, and the possible correlation between drift card studies and simulated particle movement in the eastern basin using a surface current model.

Biophysical Characteristics
The eastern basin is defined here as the area bounded by shallow sills west of Port Angeles, at Admiralty Inlet, and between Patos and Saturna Islands (Figure 1).

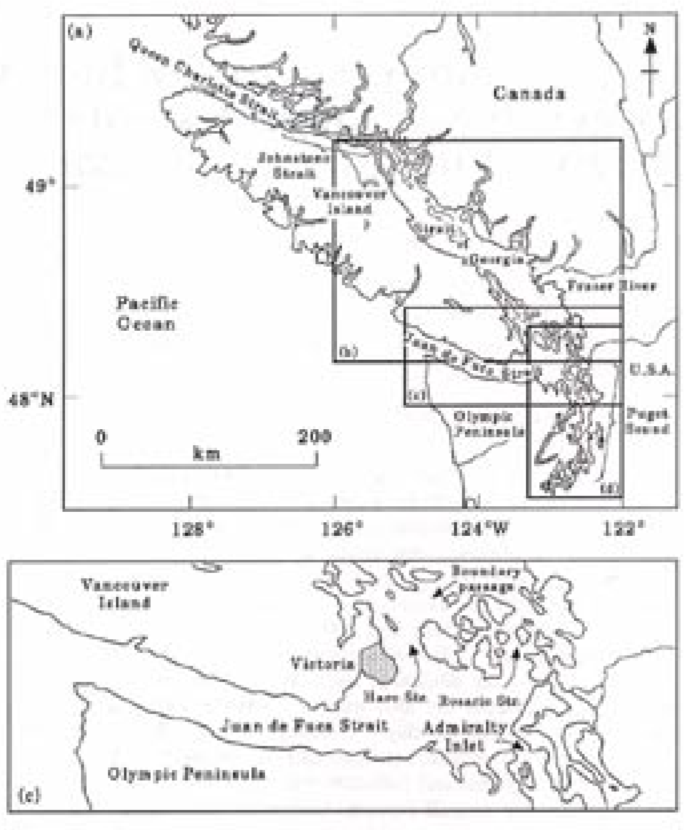

Figure 1. The Northwest Straits. Adapted from Mackas and Harrison 1997.

Oceanographically, the eastern basin is a convergence zone where waters from Puget Sound, Georgia Strait, and Juan de Fuca Strait meet, connected across relatively shallow sills and restricted passages, with a maximum depth of 420m (Mackas and Harrison 1997). Vigorous mixing and reflux is known to occur at the Victoria Sill, Boundary Passage, Active Passage, and Rosario Strait, among other locations (Masson and Cummings 2000). Because of this, stratification is weaker here than in the outer (western) Straits, with greater mixing of lower salinity water from the top layer and deeper, saltier Pacific Ocean water, also resulting in higher nutrient levels in the euphotic zone.

Ecologically, this is an important area, containing a diverse group of species, including migratory marine populations such as Pacific salmon and killer whales. Many of these have experienced dramatic declines over recent years. A 1997 report by West classified 13 populations throughout greater Puget Sound "in decline and need of recovery." This trend may be indicative of a larger regional decline in populations such as Pacific salmon, herring, and marine mammals.

Even with the paucity of empirical data on recruitment processes, it is obvious that recruitment is an important determinant of population dynamics in marine systems. Recruitment limitation may explain why many marine populations are held chronically below carrying capacity (Warner et al 2000). Recruitment failure may lead to decline in many benthic invertebrate and demersal fish populations, independent of local fecundity (Caley et al 1996). Larval retention is one important determinant of recruitment, and aggregated dispersal affects population structure over time (Largier 2003). Previous researchers have used drift cards to identify shoreline areas where passive particles are likely to accumulate (Klinger and Ebbesmeyer 2001). Among the findings of these authors and others (e.g., Pashinski and Charnell 1979) were that particle accumulation was highly variable. For example, Klinger and Ebbesmeyer (2001) found that for drift cards released within the SJA 70% were recovered on just 15% of the shoreline.

Trimble (2002; and unpub.) expanded this work by constructing a surface circulation model based on the Foreman model (Foreman et al 1995) in which virtual drifters were released from the shoreline sites used by Klinger and Ebbesmeyer (2001). We expanded this work by using Trimble's model to simulate the movements in central (offshore) regions of the eastern basin.

Figure 2. Drop sites of virtual particles. North (N) = San Juan South, South (S) = Dungeness Spit, East (E) = Whidbey Island, Central (C) = Smith Island.

Previous work has focused on accumulations in shoreline areas. Results for this work suggest that processes important to larval retention and dispersal may be occurring at various levels in the central region of the eastern basin. Drifters appear to accumulate in three prominent regions in the SJA (Rosario Strait, the Middle Channel and Haro Strait/Boundary Pass) irrespective of where they are initially released (Klinger and Ebbesmeyer 2001). This implies that localized retention may occur. Drifters also are relatively evenly distributed along the rim of the basin. This suggests that drifters entering the SJA circulate with the currents, tides, and eddies, and are ultimately dispersed relatively evenly along the surrounding shorelines.

The hypothesis that the eastern basin functions as a larval collection and redistribution zone is explored in this study; computer modeling is used to investigate these potential larval linkages. Our objectives are to answer the following questions: (1) What are the potential larval linkages in the SJA and the eastern Strait of Juan de Fuca?, and (2) What are the implications for MPA design in the eastern basin, and are there patterns that would aid in protected area design?

Methods

Virtual particles were released in four locations in the eastern basin to explore offshore circulation patterns. Each of the four locations consisted of grid points where multiple particles were released. All grids were placed slightly offshore and in four quadrants around the basin, in accordance with our intention to examine the dynamics of the central basin. The four release locations were: (1) San Juan South [northern location], (2) Whidbey Island [eastern location], (3) Smith Island [central location], (4) Dungeness Spit [southern location] (Figure 2).

One virtual particle was released from each grid every hour for 12 hours, approximately the length of one full tidal cycle, and those particles were followed for one week within a matrix of surface current velocities. Particle pathways and endpoints were mapped for each run. Using the same starting conditions, the model was run again for four weeks, to explore the approximate time period that many larval species spend in the water column.

The tidal circulation model is a modification of a model developed in FORTRAN, to predict surface tidal heights and currents (Foreman et al 1995). The original matrix of velocities was generated from a tidal model for a three month time period from April to June 2001. Resulting coordinates for the pathways and endpoints were then mapped onto the area using Matlab. We analyzed the results in the context of previous findings from drift card research, to compare across studies.

Conditions and Assumptions
The model does not account for larval behavioral characteristics, the effects of the physical forcings of wind and river inputs, or currents below three meters.

There is increasing evidence that larval behavior contributes to local retention. Studies in tropical regions have shown that current models are more likely to *overestimate* larval dispersal than underestimate it (Roberts 1997; Warner et al 2000); therefore, it follows that the dispersal envelopes generated in this model can be considered as areas of maximum dispersal.

Wind and river effects are known to be very important physical forcings in the area (Foreman et al 1995; Holbrook et al 1980) and as such, they may play a pivotal role in larval distribution in the eastern basin. The model lacks these inputs, although its initial predictions were tested against observations at tide gauge sites and current meters throughout the area for accuracy (Foreman et al 1995).

Each matrix node averages velocities from the surface to 3 m depth, and given the general homogeneity of the area within the majority of the depth that larvae occupy, surface tidal movements serve as a reasonable substitute for the water column.

Results

Central (Offshore) Areas
All virtual endpoints were analyzed according to release site. After one week, there was a greater proportion of virtual particles remaining offshore than landing onshore at all sites except Whidbey Island (see Table 1). The majority of endpoints remained offshore after four weeks as well. All endpoints remained within the study area, resulting in 100% retention of particles within the basin. For each release location, the percentage of virtual particles remaining offshore was: (1) San Juan South, 59.3% [64/108]; (2) Whidbey Island 40.9% [54/132]; (3) Smith Island 86.1% [93/108]; and (4) Dungeness Spit 74.6% [206/276].

There were strong localized movements in several offshore areas, especially at the southern ends of both Haro and Rosario Straits, the boundary area between the eastern and western sides of the Juan de Fuca Strait, and the entire western coastline of Whidbey Island.

Shoreline areas close to the four virtual drop sites displayed strong retention (Figure 3). At Smith Island, few virtual endpoints landed on the actual shore, although the majority remained quite near the northwest shore. The dominant tidal influence is apparent from the lateral movements of virtual particles in the surface water. Simulations show that after four weeks, the same general pattern of particle distribution is still evident, with some expansion, particularly northward to the Georgia Basin.

Table 1. Virtual particle endpoint distribution after one week.

Location	Onshore Landings	Central Landings	Total
San Juan South	44 (40.7%)	64 (59.3%)	108
Dungeness Spit	70 (25.4%)	206 (74.6%)	276
Whidbey Island	78 (59.1%)	54 (40.9%)	132
Smith Island	15 (13.9%)	93 (86.1%)	108

Nearshore Areas
There appears to be some variability in onshore landings, both in area and percentage total. Of the total virtual particles, the percentage that landed onshore for each release location were: (1) San Juan South, 40.7% [44/108]; (2) Whidbey Island 59.1% [78/132], (3) Smith Island 13.9% [15/108], and (4) Dungeness Spit 25.4% [70/276]. Particle trajectories reveal a strong trend in retention along most shorelines; lateral-tending trajectories may reflect the strong, dominating tidal influence in the area (Figure 4, Table 1).

This analysis is consistent with the existence of four areas of larval accumulation identified in previous drift card studies (southern shore of Lopez Island, Dungeness Spit, the area around Victoria, and the northwest shore of Whidbey Island).

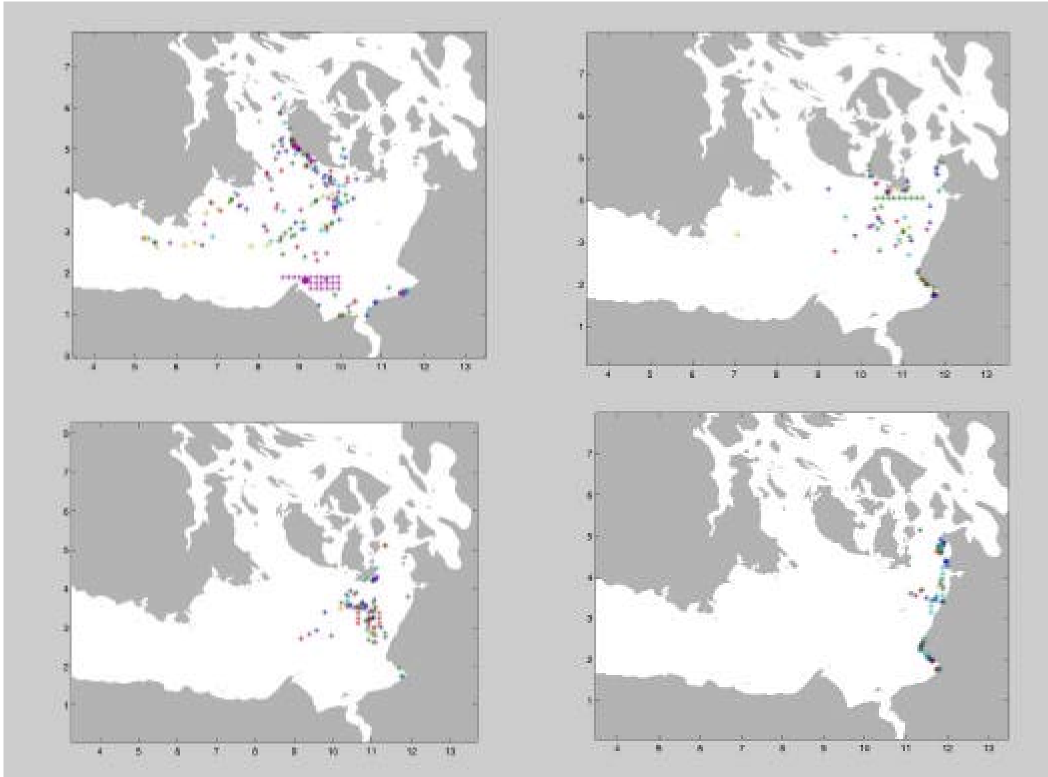

Figure 3. Trajectories of the four virtual release sites after one week, clockwise from left: Dungeness Spit, San Juan South, Whidbey Island, and Smith Island.

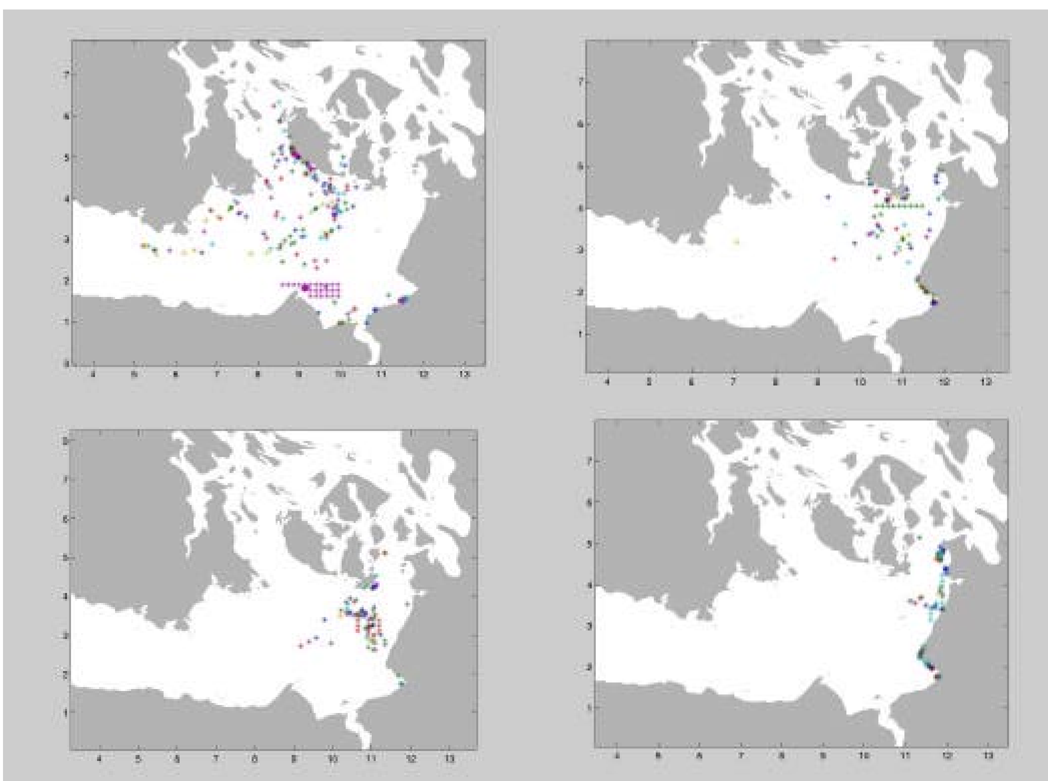

Figure 4. Virtual particles after one week simulations. The four locations are, clockwise from left: Dungeness Spit, San Juan South, Whidbey Island, Smith Island.

In addition, the southwest shore of Whidbey Island and the western side of San Juan Island accumulated large numbers of virtual particles.

Discussion

In drift card studies it is only possible to obtain data regarding the ultimate stranding location of the cards along the shoreline; little can be inferred about trajectories or the possible presence of offshore accumulation zones. Our results indicate that scale and variability should be addressed in discussions of onshore accumulation and offshore retention.

Scale

It appears that the scale of linkages is localized within the basin, with east and west quadrants showing different surface movement patterns. Also, even after one month, there was particularly strong retention of virtual particles within the basin. *All* particles remained in the study area. We recognize that this result might not have been obtained if wind and river forcings were included in the model. Even so, the strong influence of the tides is obvious from the particle trajectories. The resultant dispersal patterns indicate that larvae might be locally retained; especially if larval behavior modifies passive drift in the direction of *greater* local retention.

Variability

The effect of topography, bathymetry and coastlines on larvae is obvious, and an area of active investigation (e.g., Klinger and Ebbesmeyer 2001; Warner et al 2000; Wolanski and Hamner 2002). Certain coastlines in the eastern basin appear to be areas of high potential accumulation: the four locations indicated from previous studies (the area around Victoria, southern Lopez Island, northwest Whidbey Island, and Dungeness Spit), and two additional areas indicated here (southwest Whidbey Island and western San Juan Island).

This finding corresponds with results from oceanographic studies. The two virtual release sites with the highest onshore landings were Whidbey Island and San Juan South. Strong currents are known to occur at both of these places, going south from Rosario Strait and north through Boundary Passage, respectively. And as Klinger and Ebbesmeyer (2001) noted, an eastward current between Ediz Hook and Dungeness Spit interacts with tidal eddies in the leeward side and are partially responsible for the observed collection of drift cards and virtual particles in the area.

Central Retention

Our study revealed that areas within the eastern basin are likely to function as offshore retention zones. Further, we speculate that these offshore collection areas in the middle of the basin may serve as larval export areas to the rest of the SJA.

Implications for MPA Design

Post-settlement vs. Pre-settlement Protection

A number of fundamental questions underlie larval ecological studies and their application to marine management. First, is recruitment a primary limiting factor for the adult population (Warner et al 2000)? If so then we should strive to identify existing accumulation and retention zones. If not, this may be less critical. Secondly, is post-settlement habitat protection enough? Or is pre-settlement habitat also consequential to achievement of management objectives? Regardless, settlement depends on larval supply, whether originating locally or dependent on distant production, and the condition of retention/accumulation areas may influence this supply (Warner et al 2000).

Several implications for MPA design have emerged from this study. Results lead us to suggest that offshore accumulation and retention of larvae may be a prominent feature in the eastern basin. Further, these areas may be exporting larvae to nearshore habitats. We suggest that marine reserve networks should include offshore accumulation zones as well as nearshore habitats. The southwest and northwest shorelines of the basin are promising areas for pre-settlement protection of larval retention zones.

As a hydrographic zone, protection of both shoreline and central areas may provide ecological benefits to all three neighboring water bodies. Through reflux, part of the incoming flows from the north, south and west goes back to both the north and west in different water layers. Water motion, ecosystem and larval transport processes in the eastern Strait are thus tightly linked to the San Juan Archipelago, as well as to Puget Sound and the Georgia Basin. Larvae are susceptible to pollution from shipping and terrestrial activities, and, if offshore accumulation does occur as is suggested, neglecting to protect these source areas may negatively impact conservation efforts throughout the entire Northwest Straits region. High levels of retention will have the effect of magnifying positive and negative effects on populations.

Conclusion

The Foreman model as modified by Trimble allowed us to infer larval trajectories and further expand basin-wide investigations of particle movement. Simulations indicate that the eastern Straits exhibit larval linkages on a within-basin scale, as well as high levels of retention. Simulations also support evidence for potential regional ramifications due to current patterns. The physical and biological mechanisms underlying these patterns remain unresolved, but we suggest that they must be addressed before we can fully understand the complexities associated with MPA network design. Future research should aim to resolve larval trajectories in the area in attempts to identify zones of accumulation and retention, and the mechanisms responsible.

The time has now come for research that integrates nearshore habitat surveys, and oceanographic and behavioral studies. As mentioned earlier, understanding the effects of wind and river input, bathymetric features, local circulation patterns, and larval behavior, will provide us with the tools to confidently design a network of MPAs in the region. If central collection zones are indeed pre-settlement larval reservoirs, their protection is just as critical as that of post-settlement, nearshore habitats. We must not let uncertainties prevent us from taking proactive measures, and setting aside basin-wide protections in attempts to recover marine species and the habitats they need to survive.

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